

The role of AGN feedback and gas viscosity in hydrodynamical simulations of galaxy clusters

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Summary. We study the imprints of AGN feedback and physical viscosity on the properties of galaxy clusters using hydrodynamical simulation models carried out with the TreeSPH code GADGET-2. Besides self-gravity of dark matter and baryons, our approach includes radiative cooling and heating processes of the gas component and a multiphase model for star formation and SNe feedback [1]. Additionally, we introduce a prescription for physical viscosity in GADGET-2, based on a SPH discretization of the Navier-Stokes and general heat transfer equations. Adopting the Braginskii parameterization for the shear viscosity coefficient, we explore how gas viscosity influences the properties of AGN-driven bubbles. We find that the morphology and dynamics of bubbles are significantly affected by the assumed level of physical viscosity in our simulations, with higher viscosity leading to longer survival times of bubbles against fluid instabilities. In our cosmological simulations of galaxy clusters, we find that the dynamics of mergers and the motion of substructures through the cluster atmosphere is significantly affected by viscosity. We also introduce a novel, self-consistent AGN feedback model where we simultaneously follow the growth and energy release of massive black holes embedded in a cluster environment. We assume that black holes accreting at low rates with respect to the Eddington limit are in a radiatively inefficient regime, and that most of the feedback energy will appear in a mechanical form. Thus, we introduce AGN-driven bubbles into the ICM with properties, such as radius and energy content, that are directly linked to the black hole physics. This model leads to a self-regulated mechanism for the black hole growth and overcomes the cooling flow problem in host halos, ranging from the scale of groups to that of massive clusters.

1 Physical viscosity in SPH simulations of galaxy clusters

There is growing observational evidence [2, 3, 4] that gas viscosity in massive, hot clusters might not be negligible, and that it could play an important role in dissipating energy generated by AGN-driven bubbles or during merger events.

1.1 Numerical implementation

Within the framework of the entropy conserving formulation of SPH [5] in GADGET-2 [6, 7], we have implemented a treatment of physical viscosity that

accounts both for the shear and bulk part, as explained in detail in [8]. In particular, we have derived novel SPH formulations of the Navier-Stokes and general heat transfer equations, and for the shear viscosity coefficient we have adopted Braginskii’s parameterization [9, 10]. We have tested our numerical scheme extensively on a number of hydrodynamical problems with known analytic solutions, recovering these solutions accurately.

1.2 AGN-driven bubbles in a viscous ICM

As a first application of our physical viscosity implementation in GADGET-2, we have analyzed AGN-induced bubbles in a viscous intracluster gas. We consider models of isolated galaxy clusters consisting of a static NFW dark matter halo with a gas component which is initially in hydrostatic equilibrium. AGN heating has been simulated following a phenomenological approach, outlined in [11], where the bubbles are recurrently injected in the central cluster region. In Fig. 1 we show temperature maps of a $10^{15} h^{-1} M_{\odot}$ galaxy cluster that is subject to AGN heating and has a certain level of physical viscosity. In the left-hand panel, the Braginskii viscosity has been suppressed by a factor of 0.3, while in the right-hand panel, the simulation has been evolved with the full Braginskii viscosity. It can be seen that the morphologies, maximum clustercentric distance reached and survival times depend strongly on the assumed level of physical viscosity. With unsuppressed Braginskii viscosity, bubbles rise up to $\sim 300 h^{-1} \text{kpc}$ in the cluster atmosphere without being disrupted, and up to 2 – 3 bubble episodes can be detected, indicating that the bubbles survive as long as $\sim 2 \times 10^8 \text{yr}$. However, in the case of suppressed physical viscosity by a factor of 0.3 bubbles start to disintegrate at roughly $150 h^{-1} \text{kpc}$.

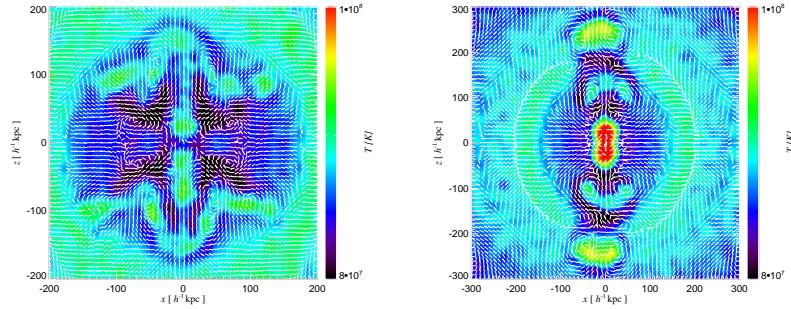


Fig. 1. Mass-weighted temperature maps of a $10^{15} h^{-1} M_{\odot}$ isolated halo, subject to AGN bubble heating. The velocity field of the gas is over-plotted with white arrows.

1.3 Cosmological simulations of viscous galaxy clusters

We have carried out fully self-consistent cosmological simulations of galaxy clusters with certain amounts of physical viscosity. We have both performed viscous non-radiative simulations and runs with additional cooling and star formation, in order to understand the complex interplay of these different physical ingredients. In Fig. 2 we show density maps of a non-radiative galaxy cluster simulation at $z = 0.1$ without any physical viscosity (left-hand panel) and with 0.3 of Braginskii shear viscosity (right-hand panel). We find that the introduction of a modest level of physical viscosity has a significant impact on galaxy cluster properties. The dynamics of clusters during merging events is affected, with viscous dissipation processes generating an entropy excess in cluster peripheries. Also, due to the viscous dissipation, smaller structures entering more massive halos are more efficiently stripped of their gaseous content, which forms narrow and up to $100h^{-1}\text{kpc}$ long tails, as visible on the right-hand panel of Fig. 2. These features of viscous dissipation are very prominent, occurring already at quite early cosmic times and regardless of the presence of radiative cooling in the runs. However, even though viscous dissipation occurs in the central cluster region, it does not provide sufficient heating to prevent the formation of a central cooling flow at low redshifts, indicating that at least one other physical process is needed to reconcile observational findings with simulations.

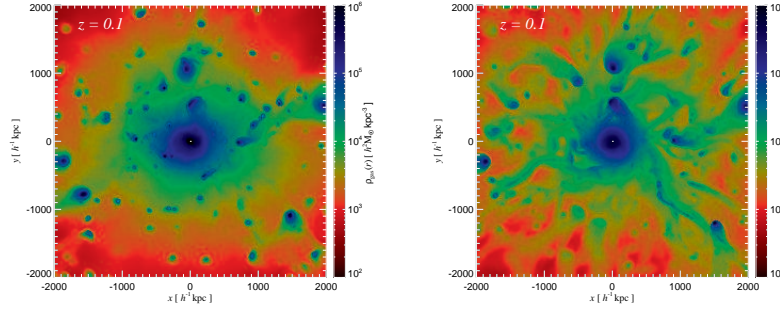


Fig. 2. Projected gas density maps of a galaxy cluster simulation at redshift $z = 0.1$, as indicated in the upper-left corner of the panels. The left-hand panel shows the gas density distribution in the case of a non-radiative run, while the right-hand panel gives the gas density distribution when Braginskii shear viscosity is “switched-on”, using a suppression factor of 0.3.

2 Self-regulated AGN feedback in simulations of galaxy clusters

2.1 Methodology

We have developed a novel AGN feedback model that simultaneously tracks the growth of massive black holes in cluster environments, and provides heating in the form of AGN-driven bubbles [12]. In our simulations of clusters a self-regulated feedback loop is established, leading to an equilibrium where black hole growth is restricted and the central ICM is heated, overcoming the cooling flow problem.

We model the black hole growth according to the prescriptions outlined in [13, 14]. In these studies, the Bondi formula has been adopted for the accretion rate onto a black hole, and the Eddington limit has been imposed. Here, we link the black hole properties, namely its mass and accretion rate, with the physics of AGN-blown bubbles. We parameterize our scheme in terms of bubble energy and radius, and we consider recurrent episodes of bubble injection. Specifically, we introduce a threshold in black hole accreted mass above which a bubble event is triggered. We relate the bubble energy with the black hole properties as follows,

$$E_{\text{bub}} = f \epsilon_r c^2 \delta M_{\text{BH}}, \quad (1)$$

where f is the fraction of energy that goes into the bubbles¹, ϵ_r is the standard radiative efficiency that we assume to be 0.1, and δM_{BH} is the mass growth of a black hole between two successive bubble episodes. Moreover, we link the bubble radius both to δM_{BH} and to the density of the surrounding ICM, in the following way

$$R_{\text{bub}} = R_{\text{bub},0} \left(\frac{E_{\text{bub}}/E_{\text{bub},0}}{\rho_{\text{ICM}}/\rho_{\text{ICM},0}} \right)^{1/5}, \quad (2)$$

where $R_{\text{bub},0}$, $E_{\text{bub},0}$, and $\rho_{\text{ICM},0}$ are normalization values for the bubble radius, energy content and ambient density. The relation for the bubble radius is motivated by the solutions for the radio cocoon expansion in a spherically symmetric case [15].

2.2 Black hole growth and feedback in isolated galaxy clusters

We have performed simulations of isolated galaxy clusters for a range of different masses, from $10^{13} h^{-1} \text{M}_{\odot}$ to $10^{15} h^{-1} \text{M}_{\odot}$, analyzing the black hole growth and feedback over a large time span. The initial conditions have been set up by imposing hydrostatic equilibrium for the gas within a static NFW

¹For low accretion rates, $\dot{M}_{\text{BH}} < 10^{-2} \dot{M}_{\text{Edd}}$, we assume that most of the energy is in mechanical form.

dark matter halo, and by introducing a seed black hole sink particle with $10^5 h^{-1} M_\odot$. The simulations have been evolved for $0.25 t_{\text{Hubble}}$ with radiative cooling, star formation, and AGN feedback. In the left-hand panel of Fig. 3 we show how the black hole mass is growing for three halos of increasing mass. After the initial rapid growth, bubble feedback regulates the black hole mass, which remains practically constant for more than a Gyr of the simulated time. The mass accretion rate onto the black hole (see right-hand panel of Fig. 3) drops after the initial phase to very low values of order $10^{-3} M_{\text{Edd}}$. It can be seen that the black hole accretion rate shows occasional bursts during short time intervals, reflecting the recurrent nature of the bubble feedback. However, these jumps in black hole accretion rate do not contribute significantly to the growth of the black hole itself. In Fig. 4 we plot entropy

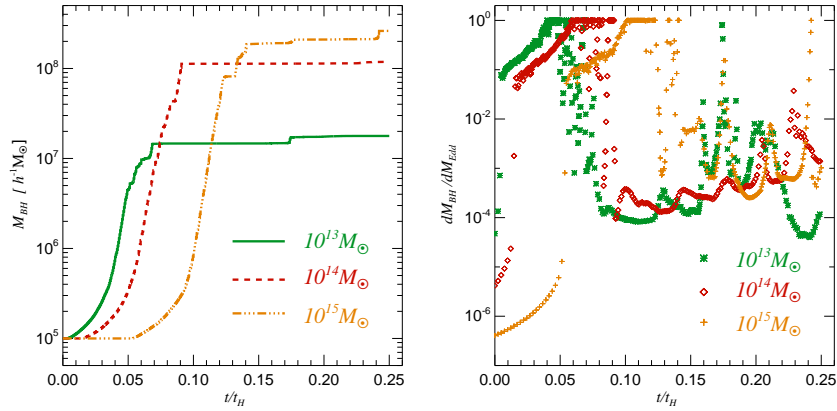


Fig. 3. Black hole mass growth and black hole accretion rate in Eddington units for three isolated galaxy clusters simulations. After the initial rapid growth from a $10^5 h^{-1} M_\odot$ seed, the black hole mass is regulated and the accretion rate drops to low values.

and temperature profiles of a $10^{14} h^{-1} M_\odot$ cluster at $0.25 t_{\text{Hubble}}$. We compare the runs without AGN heating with the simulations with different thresholds δM_{BH} for the bubble triggering. In the case of highest δM_{BH} , the bubble frequency is lowest, but the energy injected into the bubbles is large. This model corresponds to a sporadic, but rather powerful AGN activity and heats the ICM very efficiently. On the other hand, low values of δM_{BH} imply more frequent and gentle bubble feedback that affects the ICM properties mildly, but that can still prevent the overcooling in the central regions of clusters.

3 Conclusions

Unless heavily suppressed by magnetic fields, physical gas viscosity in hot, massive clusters appears to be an important physical ingredient, changing

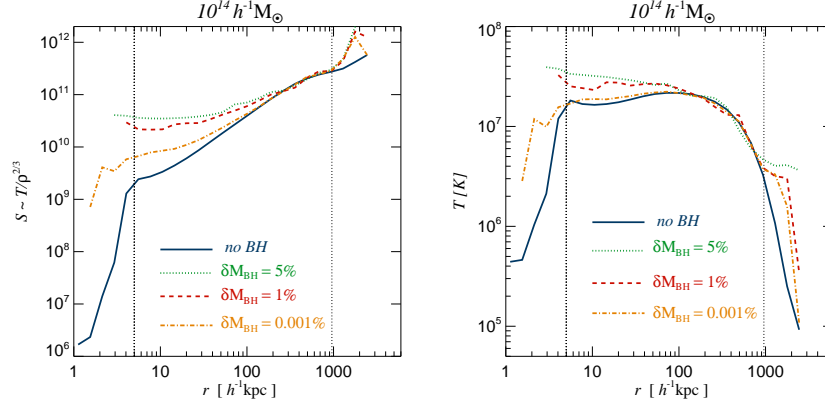


Fig. 4. Entropy (left-hand panel) and mass-weighted temperature (right-hand panel) radial profiles of a $10^{14} h^{-1} M_{\odot}$ isolated cluster. With increasing δM_{BH} bubble feedback becomes more infrequent, but also more violent, leading to a substantial heating of the central gas.

significantly the properties of AGN-driven bubbles and influencing the dynamics of clusters during merging events. The ever more accurate X-ray data on galaxy clusters will allow detailed comparisons with simulations, that can constrain the effective level of viscosity present in these systems. AGN heating is a very promising candidate to solve the cooling flow riddle in clusters. Adopting the theoretical model outlined here we discuss in forthcoming work [12] fully cosmological simulations of self-regulated AGN feedback, trying to understand this physical mechanism in more depth.

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